



“Armaments for the Army Transformation”



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# Advanced Penetrator Materials

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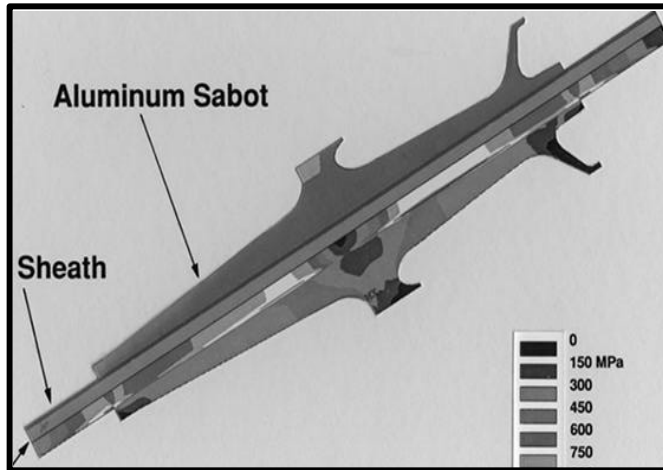
# OUTLINE



- Background: Relationships between Properties and Performance of High-Density Materials
  - the adiabatic shear failure of DU
  - general approaches to alloy development
- Uranium (U-V-X) Alloys
- Alternative Matrix (adiabatic shearing) Tungsten Composites
- Amorphous and Nanocrystalline Alloys
- Severe Deformation Processed WHAs
- Jacketed Penetrators
- Conclusions



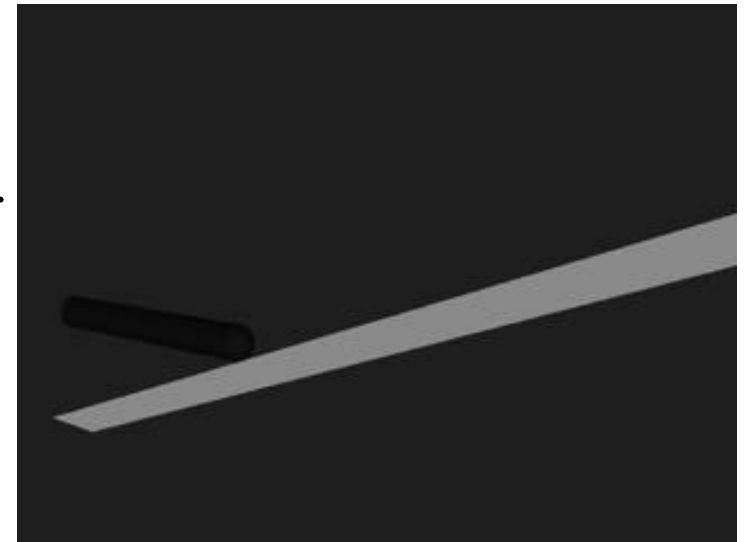
# Properties vs. Performance Relationships/Requirements



- Engineering properties: strength and toughness.
  - Allow more efficient sabots/projectiles.
  - Resist complex armors.
  - Soft-launched projectiles expand options.

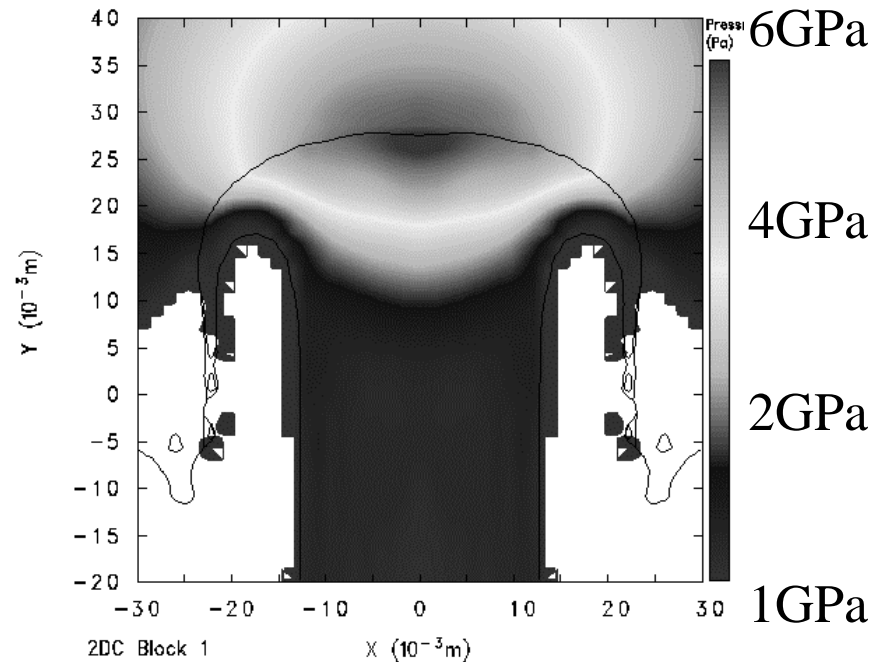
- High-rate, high pressure, deformation.
  - Controls efficiency during deep penetration.

At the present time, Depleted Uranium alloys provide the best overall combination of structural and high-rate properties.

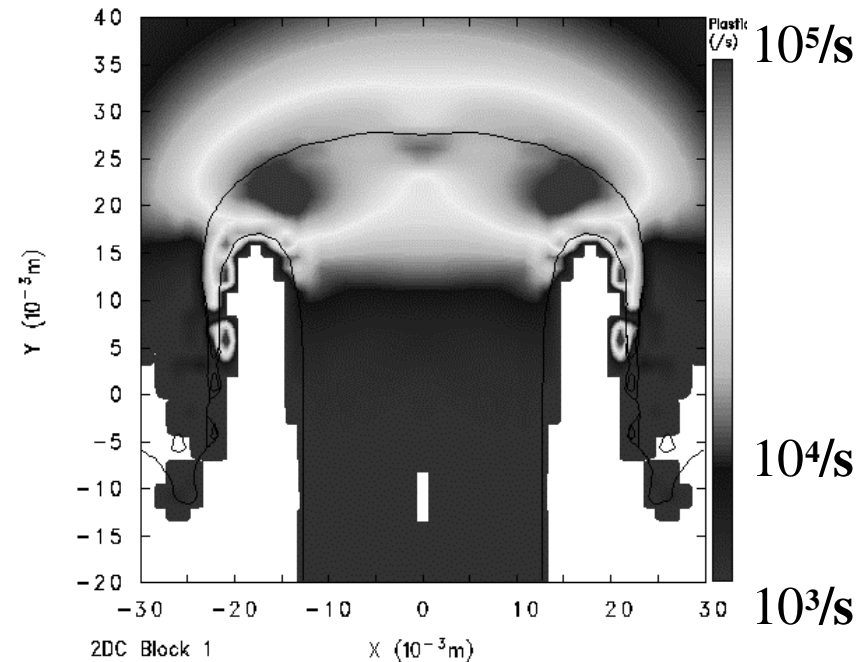




# Pressure & Strain Rate Distributions During Deep Penetration



2DC Block 1  
W alloy rod into semi-infinite RHA at 1300 m/s  
HFIFFU 08/06/98 09:01:34 CTH 466 Time= $4.00752 \times 10^{-5}$

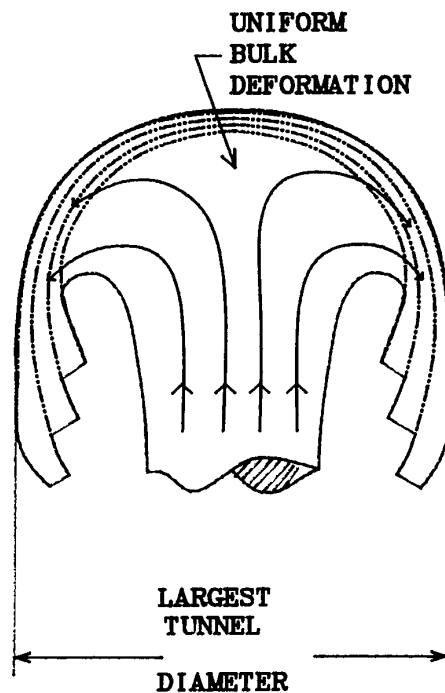


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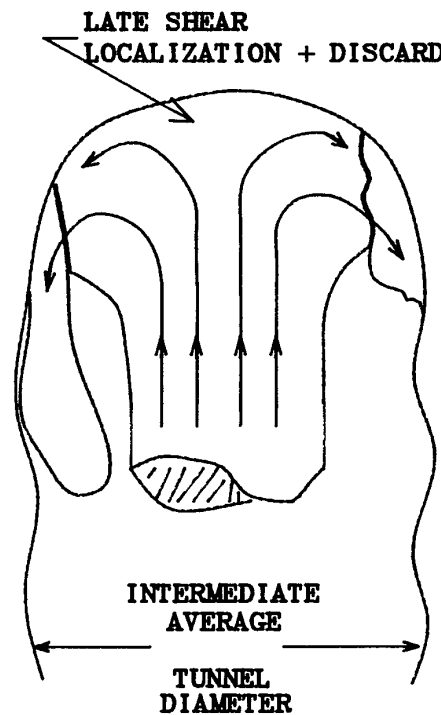
**Strain-hardening and thermal-softening mechanisms compete during the high rate (adiabatic) deformation.**



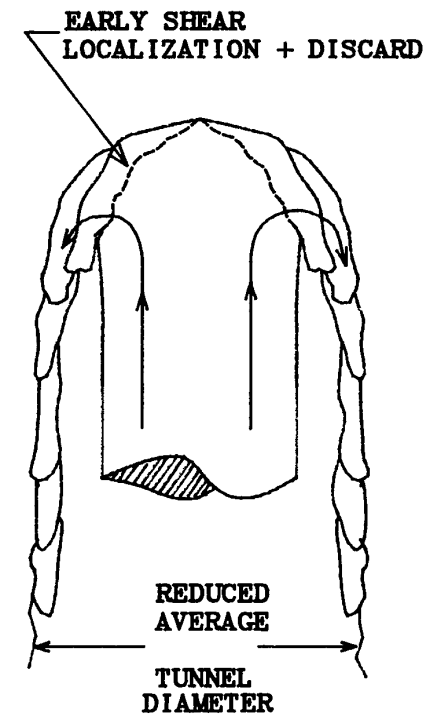
# Flow/Failure of High-Density Penetrator Materials



PURE W



CONVENTIONAL  
WHA



DU-3/4Ti

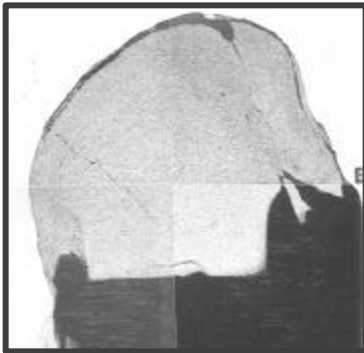
DU failure by adiabatic shear. This reduces the size of penetrator head, burrows narrower & deeper cavity.



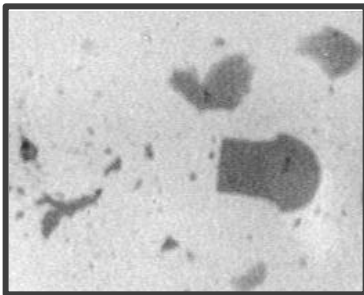
# Flow and Failure of High Density Penetrator Materials



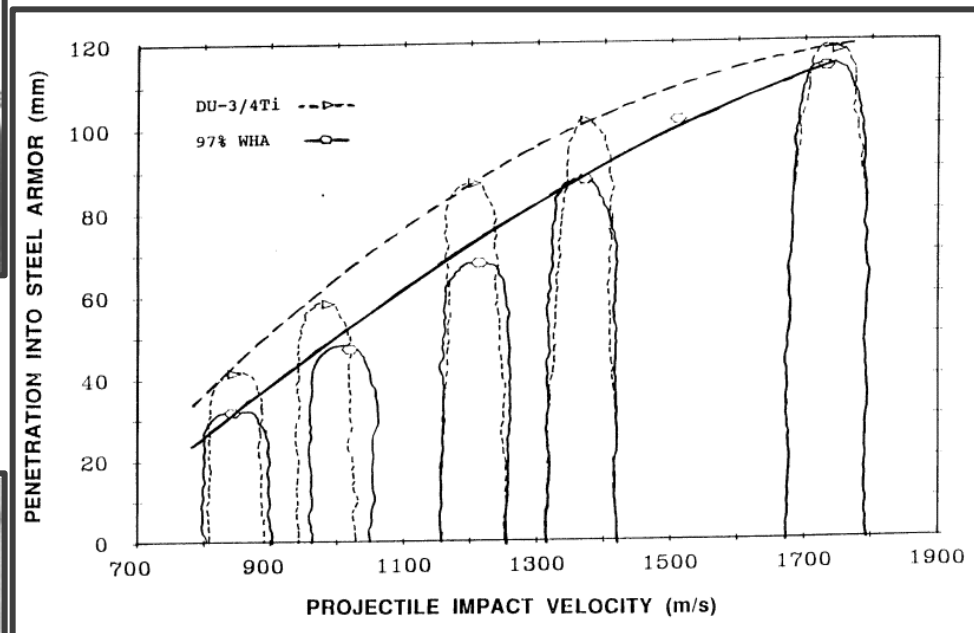
## TUNGSTEN HEAVY ALLOY



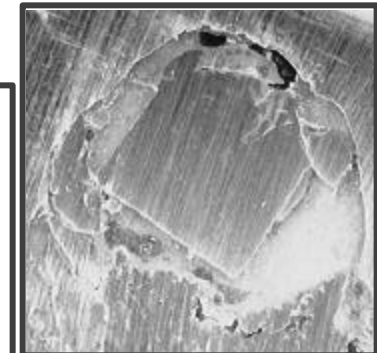
- WIDER CHANNEL
- MUSHROOM NOSE
- LESS DEPTH



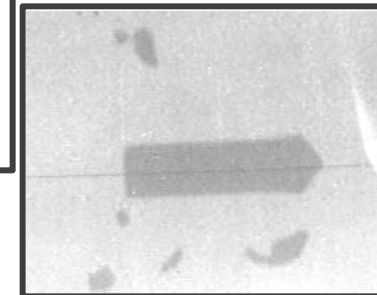
W-Ni-Fe



## U-3/4 Ti ALLOY



- REMAINS SHARP
- NARROW CHANNEL
- DEEPER CAVITY

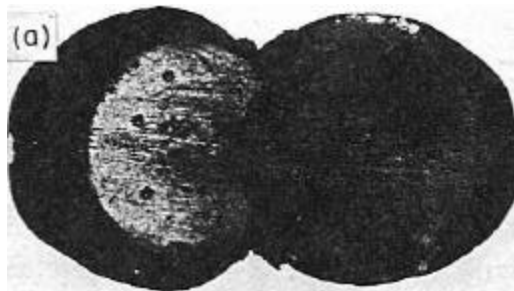
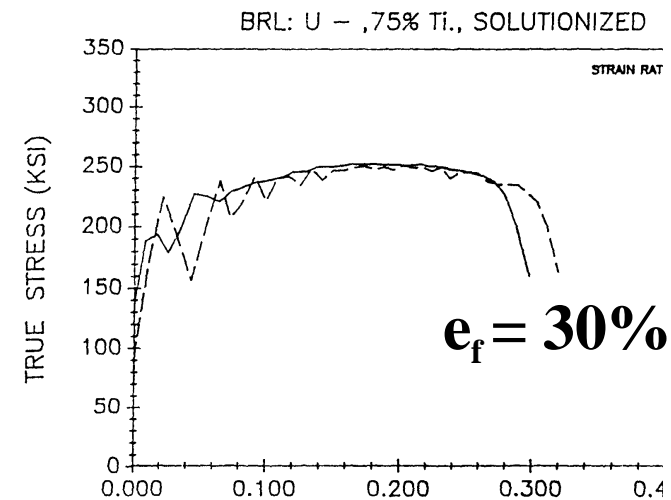
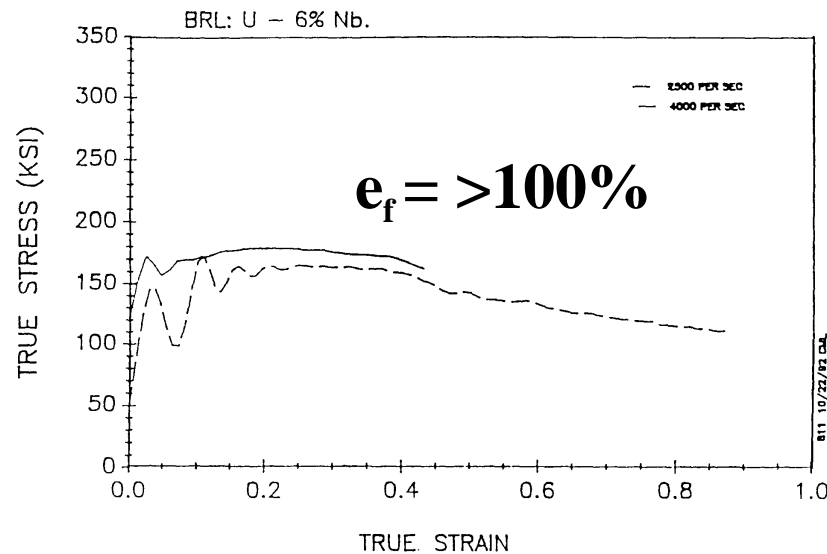


U-8Mo ALLOY



# Dynamic (SHB) Compression Tests

(strain to adiabatic shear failure)



**U-3/4Ti specimen  
cleaved by shear band**

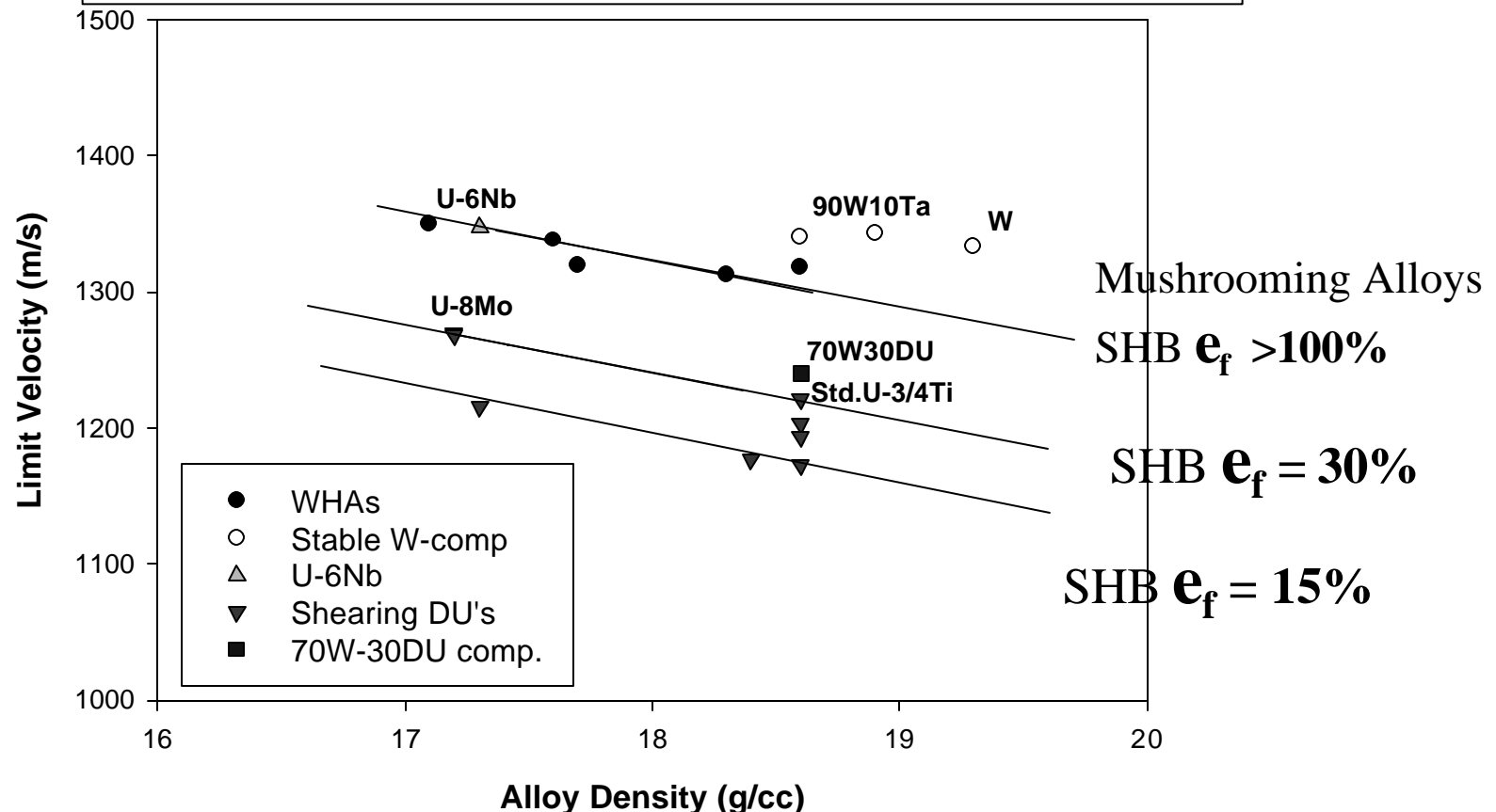
Dynamic compression experiments provide a means for assessing material failure behavior at high loading rates.



# Comparison of RHA Steel Perforation Capabilities



1/4-scale tests, 65g L/D=15 rods vs. 76.2mm RHA



**Deep Penetration performance is a function of alloy density & strain to shear failure.**





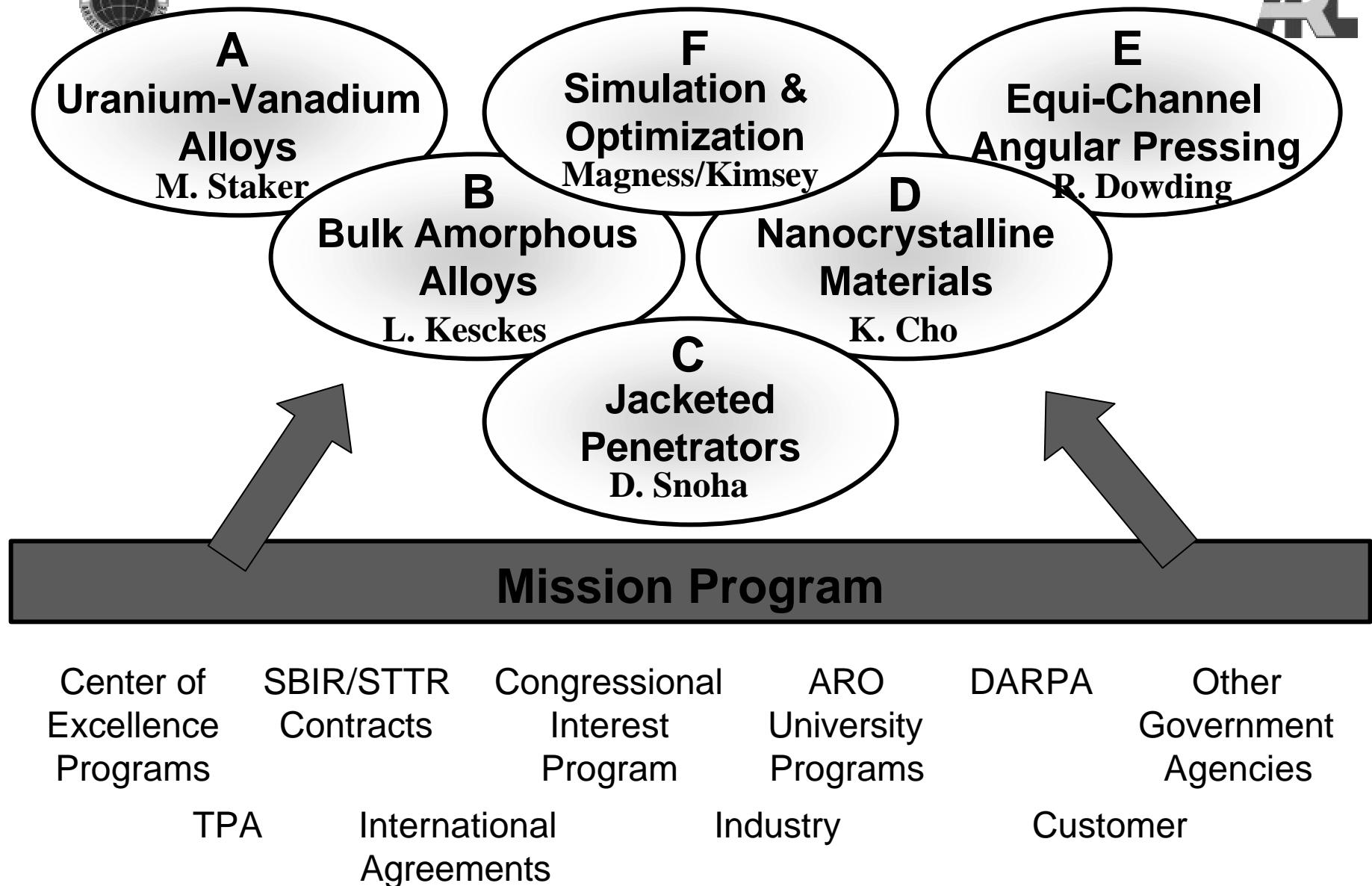
# Material Options



- **DU alloys:** Enhance susceptibility to shear failure, while retaining/improving engineering properties.
- **Non-DU materials:** change flow/failure behavior
  - Use alternative matrices, selection based on mechanical and thermal properties that promote high-rate (adiabatic) plastic instability and localization
    - Matrix alloys w/high strength, low work hardening, low strain rate sensitivity, rapid thermal softening
  - Amorphous & nanocrystalline materials as a candidate matrix alloy or entire composite (nano W phase)
    - exhibit localized shear failure in dynamic and quasi-static tests
  - Anisotropic flow/failure of W crystals
- **Jacketed Penetrators:** Systems approach, with materials issues



## CURRENT ANTI-ARMOR MATERIALS DEVELOPMENT PROGRAMS



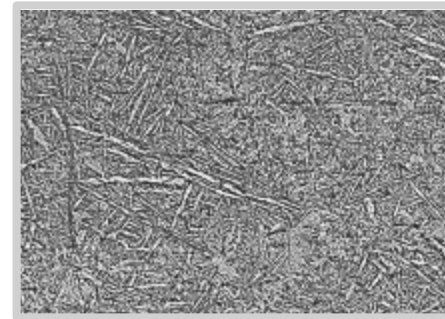
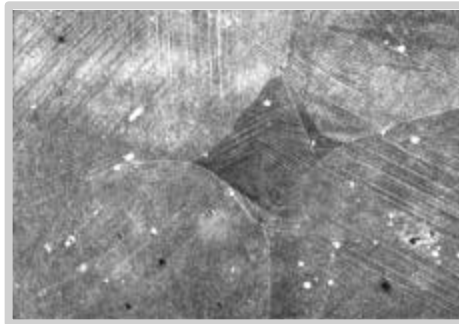


# Uranium-Vanadium Alloys



Composition	Density	Hardness	Ult. Tensile Strength
	(g/cc)	HRC	(Ksi/Mpa)
U-V (1-4.5%)	16.7–18.5	36-54	To 310/2140
U-V-X(ternary)	16-18.5	36-55	To 320/2200
U-3/4Ti	18.6	38-49	To 250/1720

U-2.1% V,  
banded  
martensite  
(from Staker)

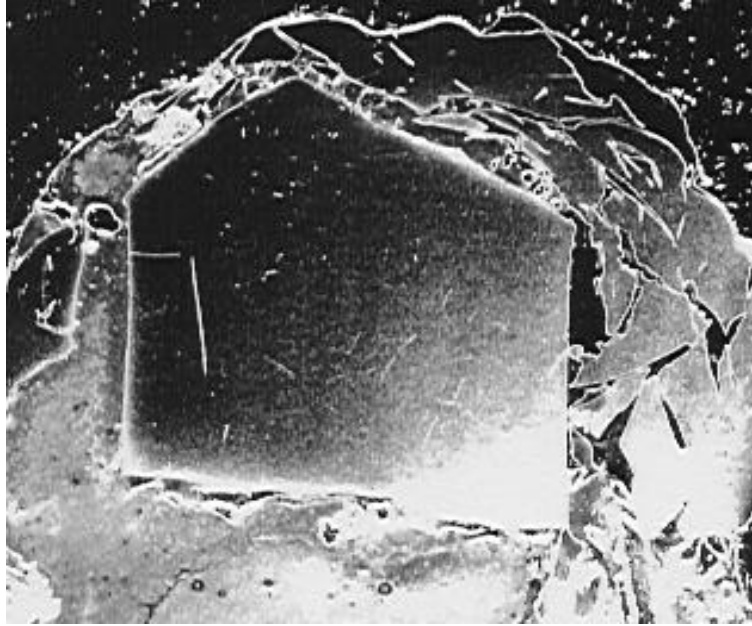


U-.75% Ti,  
acicular  
martensite  
(from Staker)

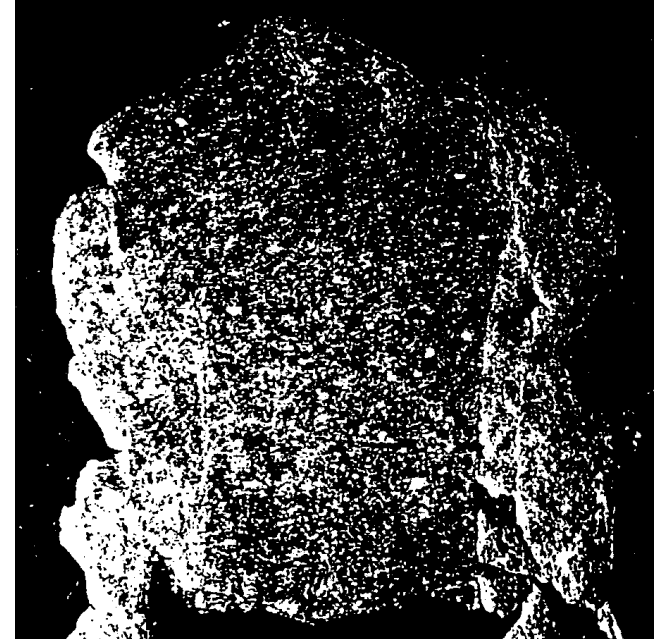
- U-V alloys have the potential to maintain penetration capability while reducing penetrator density and mass.



# Tungsten Composites with Adiabatic Shearing Matrix Alloys



**Residual Ti6Al4V Penetrator**

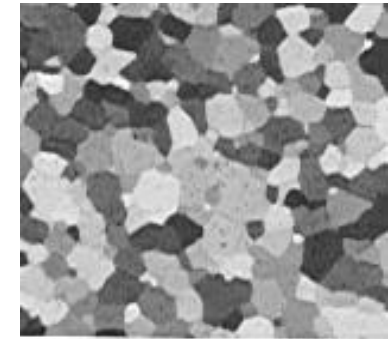
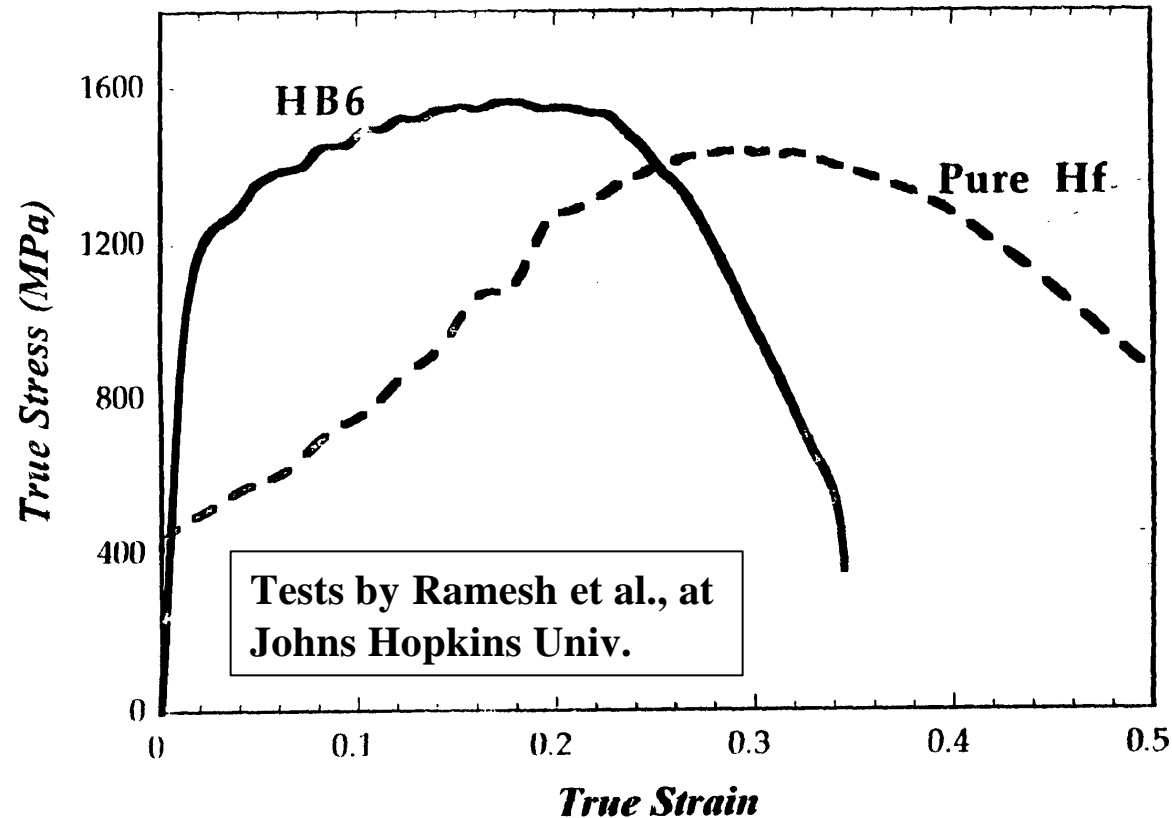


**Residual W-Ti alloy  
Composite Penetrator**

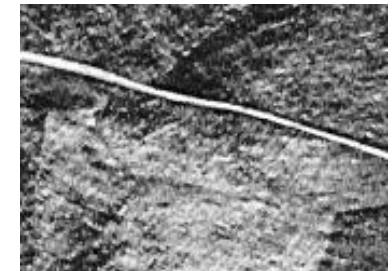
- Replace conventional Ni-Fe matrix alloy with one more prone to adiabatic shear failure, to enhance plastic instability.



# Dynamic Compression Tests of Hafnium and Hafnium Alloy



Unalloyed Hf

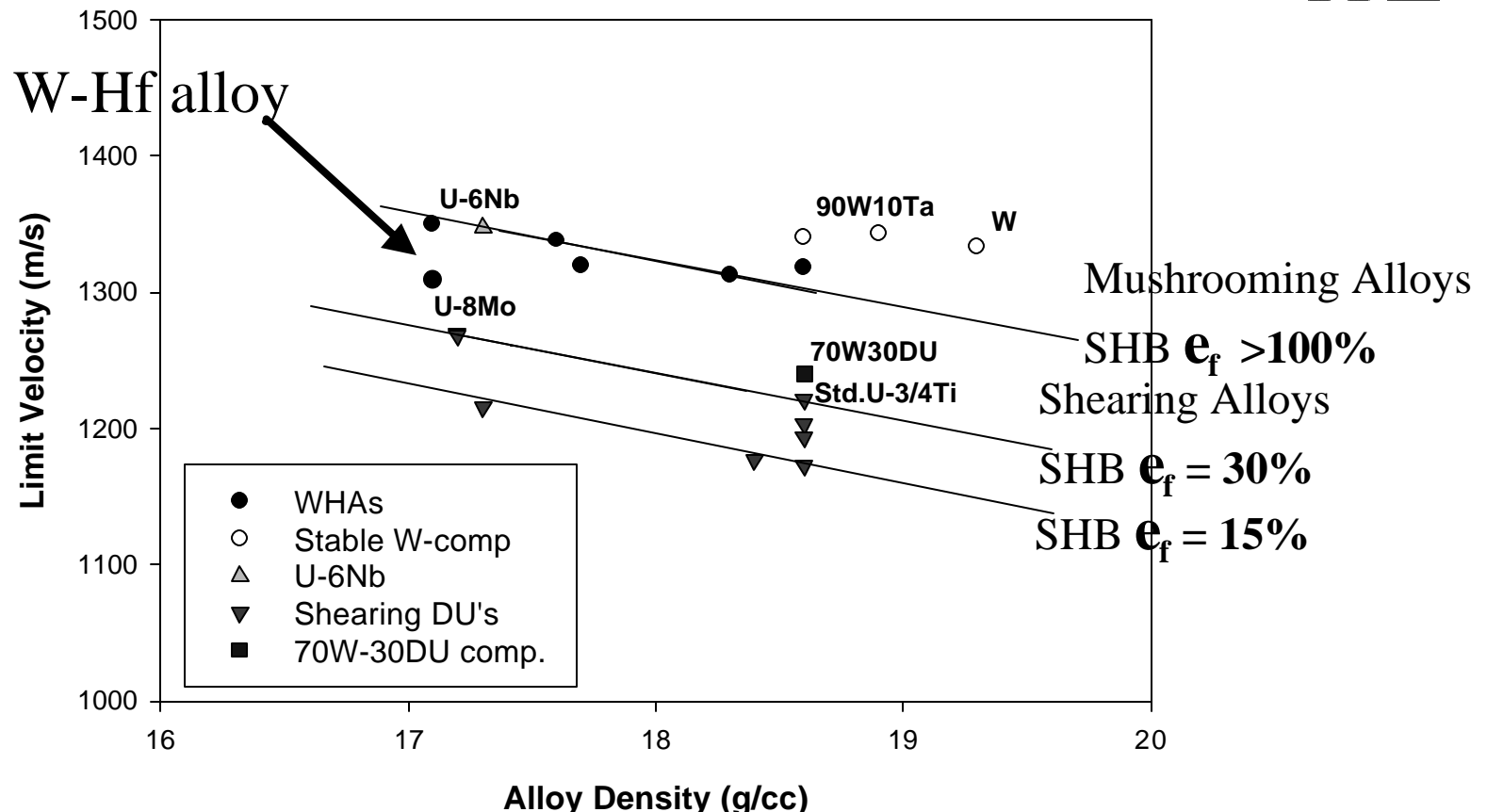


HB6, Hf10Ti10Ta

- Hafnium alloy HB6 demonstrated the preferred failure behavior in dynamic compression tests.



# Perforation of Steel



Performance of W composite with hafnium alloy matrix significantly better than conventional (Ni-Fe)-matrix WHAs, but still short of DU.

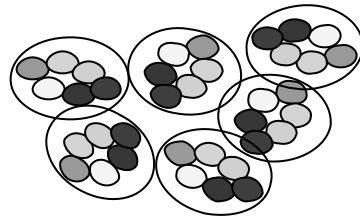
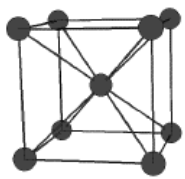


# W Composites with Bulk



## Amorphous Metal (BAM) Matrices

- Amorphous alloys lack long-range structure of crystalline solids.

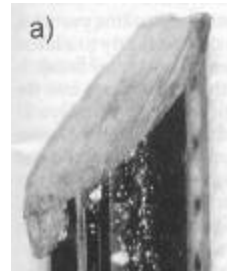
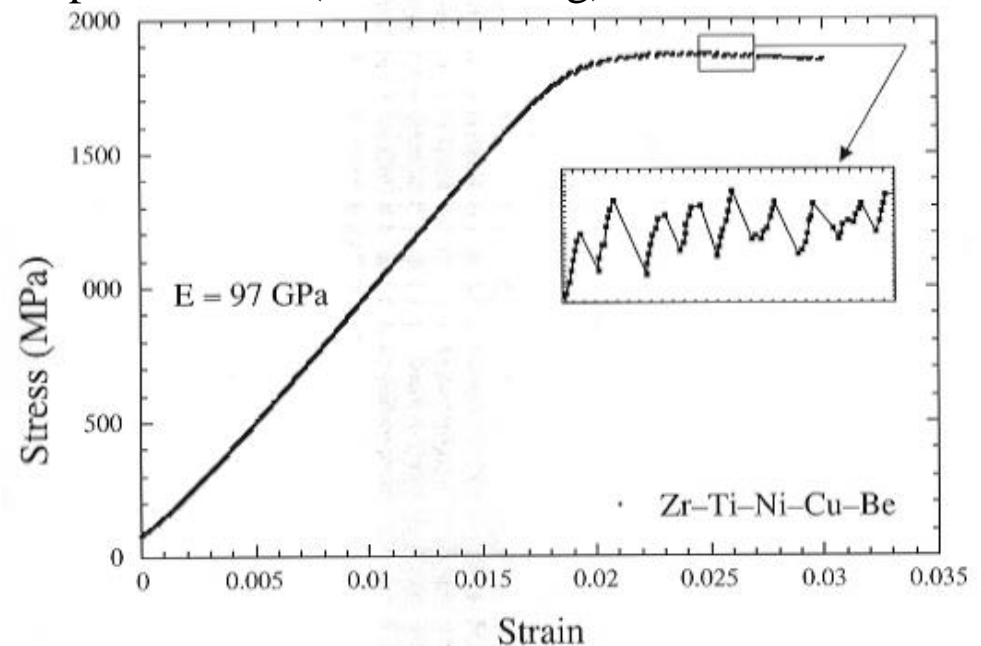


Crystalline

Amorphous

- Unique mechanical properties: high elastic limit (2-3% strain, 1.6GPa Y.S., no work-hardening).
- Recent development of complex, multi-component bulk metallic glass alloys make 1 to 5 cm thick sections possible (low quench rates)

**Typical Mechanical Behavior:** no strain hardening in quasi-static S-e curve, serrated plastic flow (shear banding)



Angled ( $\sim 45^\circ$ ) shear band failure

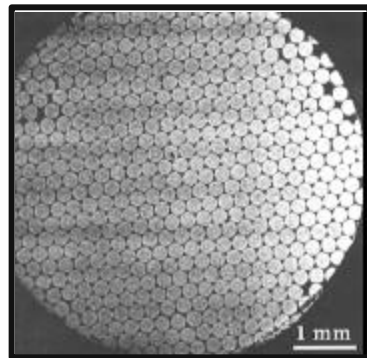
“Deformation Mechanisms of the ZrTiNiCuBe Metallic Glass”, Wright, Saha, & Nix



# W Composites with Bulk Amorphous Metal (BAM) Matrices

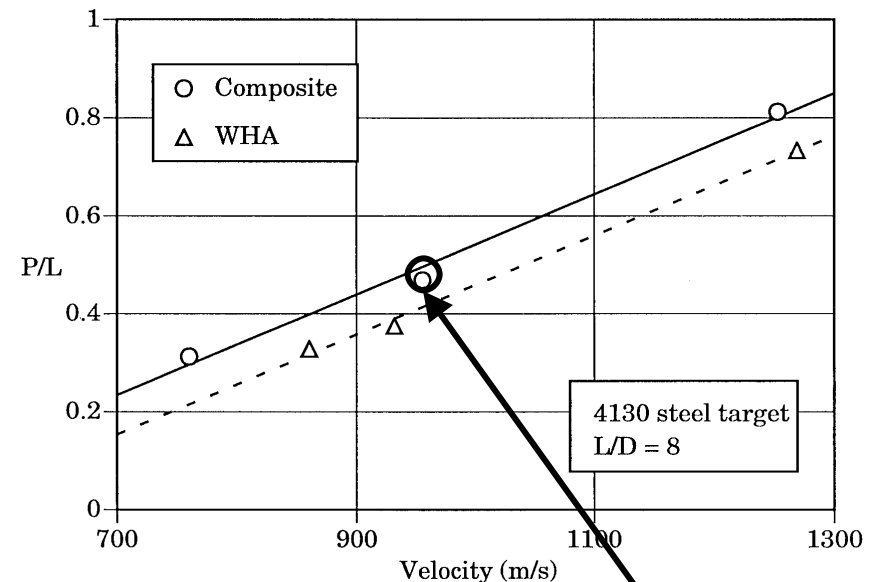


- ARO-funded CalTech development of W-composite using Z-Ti-Cu-Ni-Be bulk castable amorphous alloy



Tungsten wire/  
amorphous alloy  
composite.

80% wire  
reinforced.



Sub-scale ballistic tests  
suggest DU-like improvement  
in penetration performance.  
From ARO grant to CalTech  
(W. Johnson)



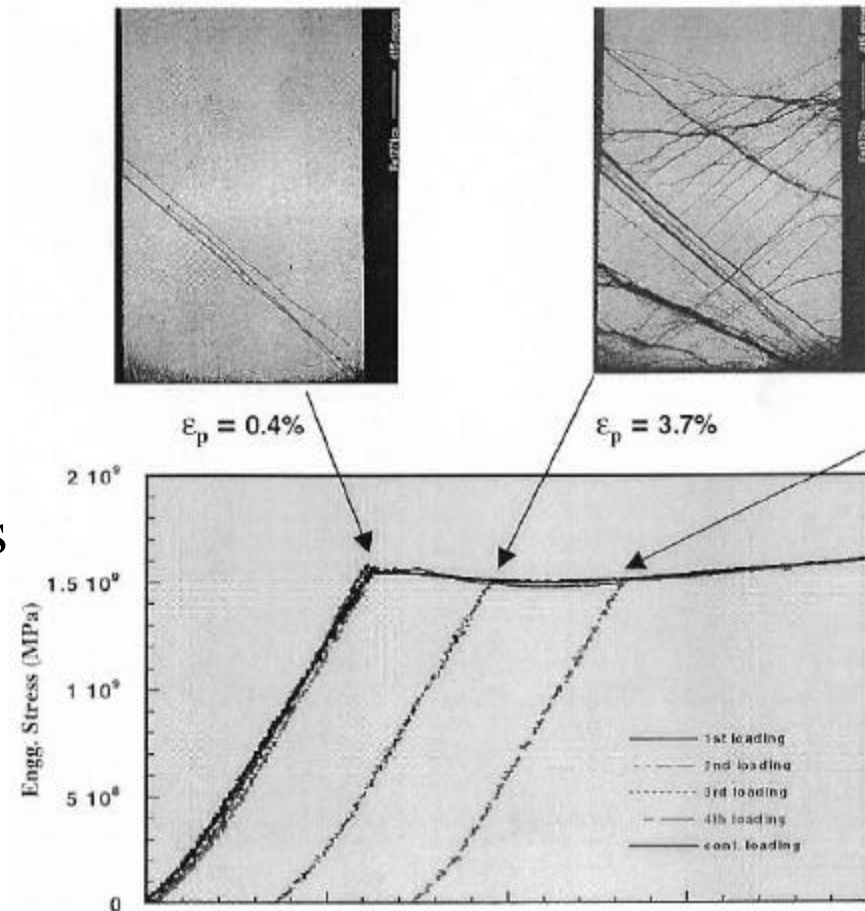




# Nanocrystalline Materials



- Like amorphous metals, nanocrystalline (<100 nm GS) metals exhibit little or no work-hardening or bulk plasticity in quasi-static tests
- Shear banding behavior has been observed in materials with GS >250 nm



Tests by Dexin Jia, of Johns Hopkins U., aver. GS 268 nm

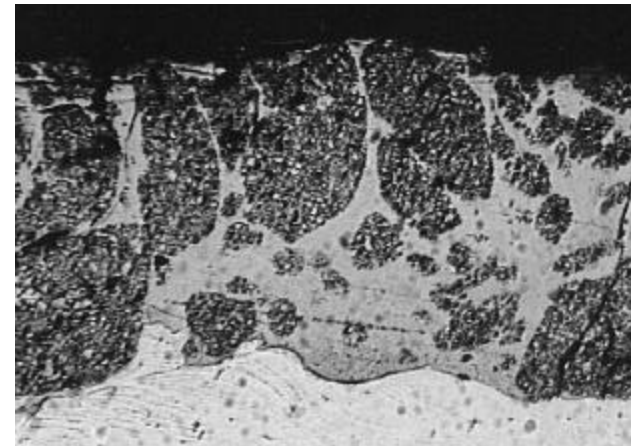


# Ballistic Tests of Nanocrystalline W-Composite



Penetrator Type	Material	Density	Limit Velocity
		(kg/m <sup>3</sup> )	(m/s)
Depleted Uranium	U-3/4 Ti, Rc 40	18600	1260
Conventional WHA	90W-9Ni-1Co	17100	1390
Nano W-Composite	W-Cu-Ni-Al	15200	1347
W-Composite w/Hf matrix	80W-20 HB3	17000	1350

- Performance of nanocomposite surpassed that of conventional WHA or best adiabatic-shearing matrix, despite lower density
- DU vs. WHA performances narrowed, but DU is still superior



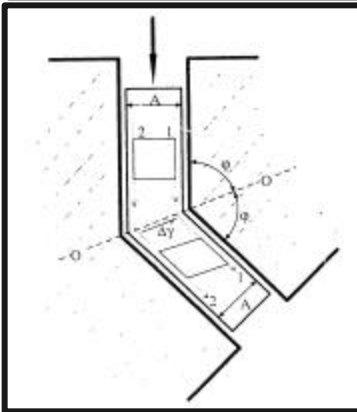
**Nano W-Composite Penetrator Erosion Products Lining Penetrator Tunnel (15X)**



# SEVERE PLASTIC DEFORMATION PROCESSING

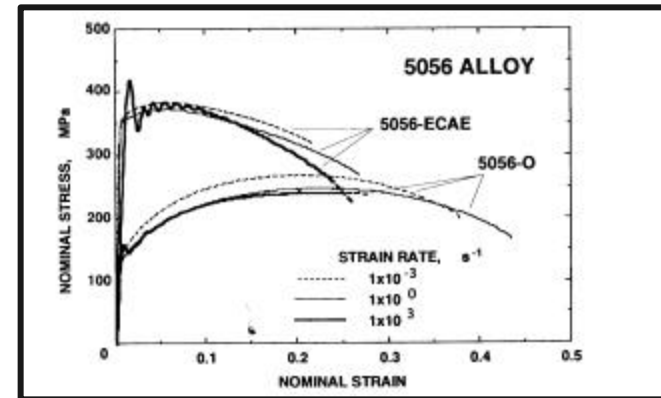
## Equi-Channel Angular Pressing (ECAP)

- New Mechanical Working Technique
- Developed in FSU
- Path to improved mechanical properties or alternative path to grain size refinement (nano)



## Key Features

- Cross section in equals cross section out.
- Pure shear deformation
- Imparts cold work (>99% ) with or w/o microstructural changes (reversible).
- Multiple passes increase deformation, refine grain size

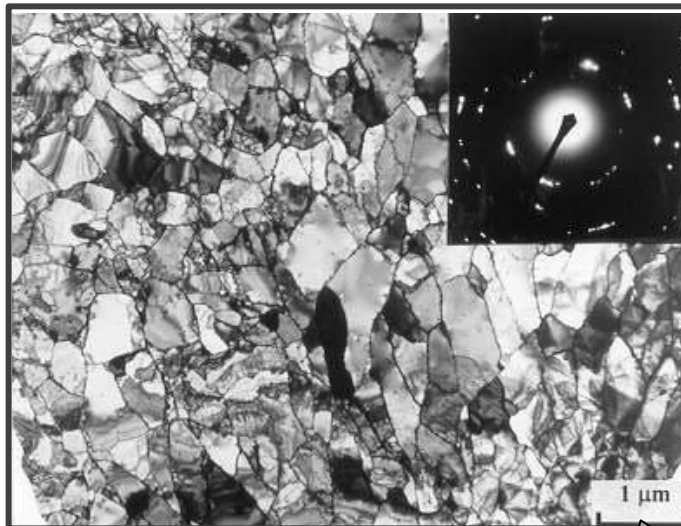


5056 Aluminum Alloy  
ECAE, >2x strength

<u>#Of Passes</u>	<u>Equiv. Reduction</u>
1	69%
2	90
4	99
8	99.99

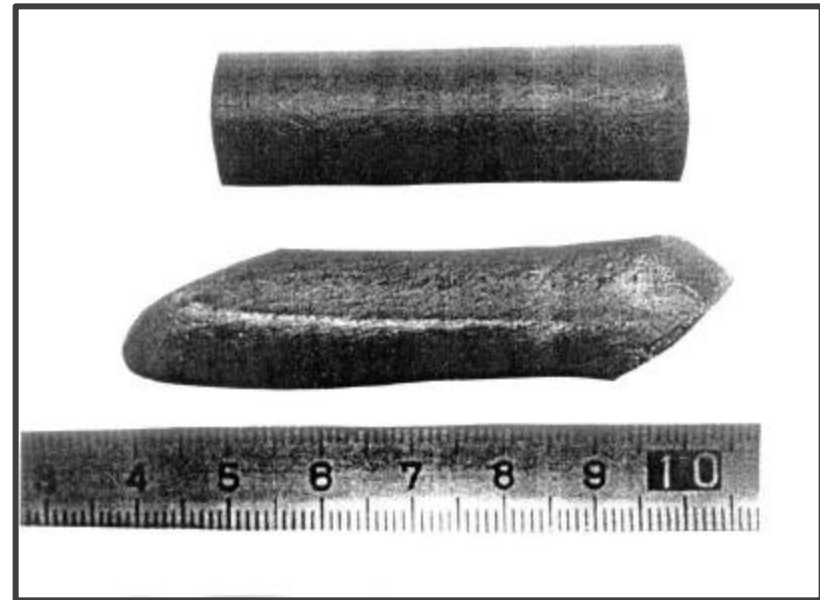


## TEM STRUCTURE AND MICRODIFFRACTION PATTERN 8 PASSES, ROUTE C



Cross Section

1  $\mu\text{m}$



Die Angle of  $110^\circ$   
Route C, 4 Passes

- Ultra Fine Grained (UFG) Structure
- Mean Grain Size Approximately  $1 \mu\text{m}$ , many grains  $0.3$  to  $0.5 \mu\text{m}$



# ***Material Bonding for Jacketed Penetrators***



**Goals: Fracture Resistance, Improved Stiffness, Reduced Mass**

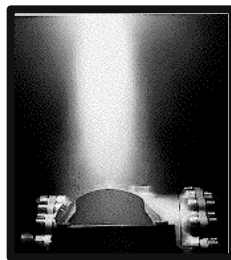


Jacket Material  
Selection and Bond  
Strength will be Key to  
success

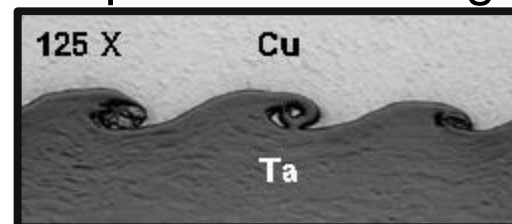


**Candidate bonding techniques guided by ballistic experiments and simulations; FOCUS – High Strength Bonds**

Thermal Spray

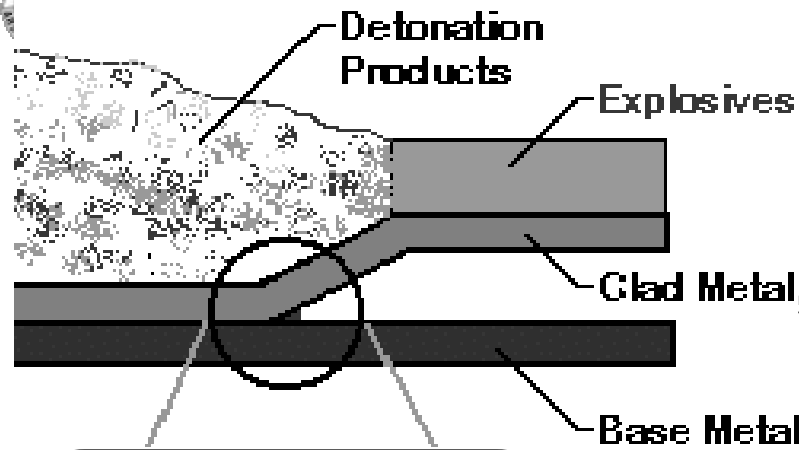


Explosive Cladding

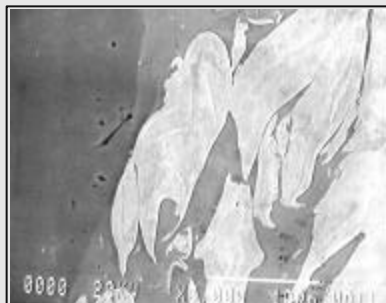




# ***Material Bonding for Jacketed Penetrators***



- ✓ Metallography
- ✓ Centerline Properties
- ✓ High Strength Bond



- High Strength Bond Achieved!
  - Subscale Experiments Pending
  - Reactive & Passive Targets
- Follow-on contract in place.
  - Full Scale Processing
- Iterate based on Ballistic Results.
- Future – Consider alternate bonding.
  - Swaging
  - Co-extrusion
  - Cold Spray



## Conclusions/Summary



- Certain minimum mechanical properties required for launch, for performance vs. complex armors
- Efficient flow & failure behaviors improve penetration performance against thick monolithic armor and individual armor components (e.g. basal armor behind ERA applique)
- Alloy development efforts must meet both goals